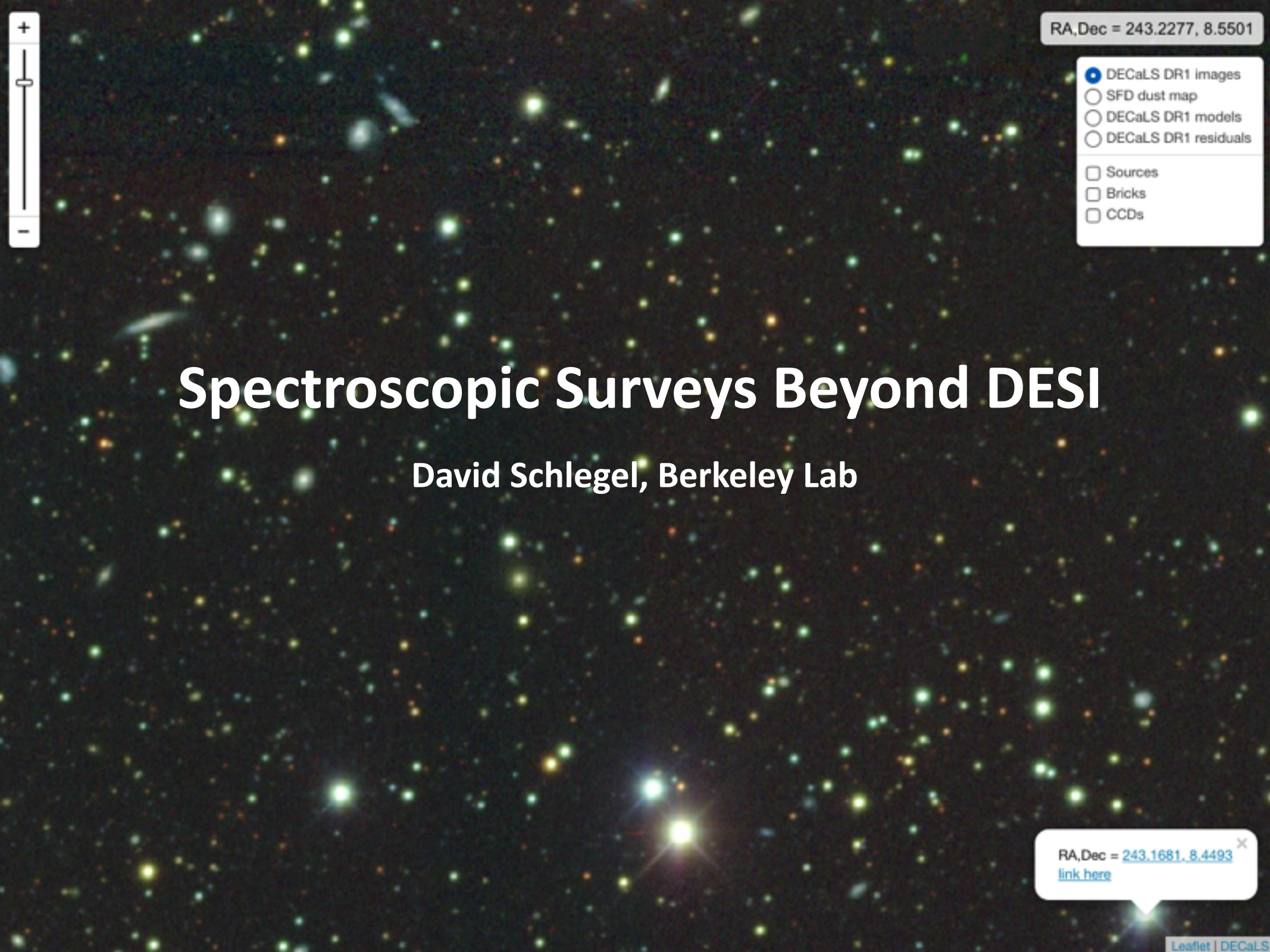


Spectroscopic Surveys Beyond DESI

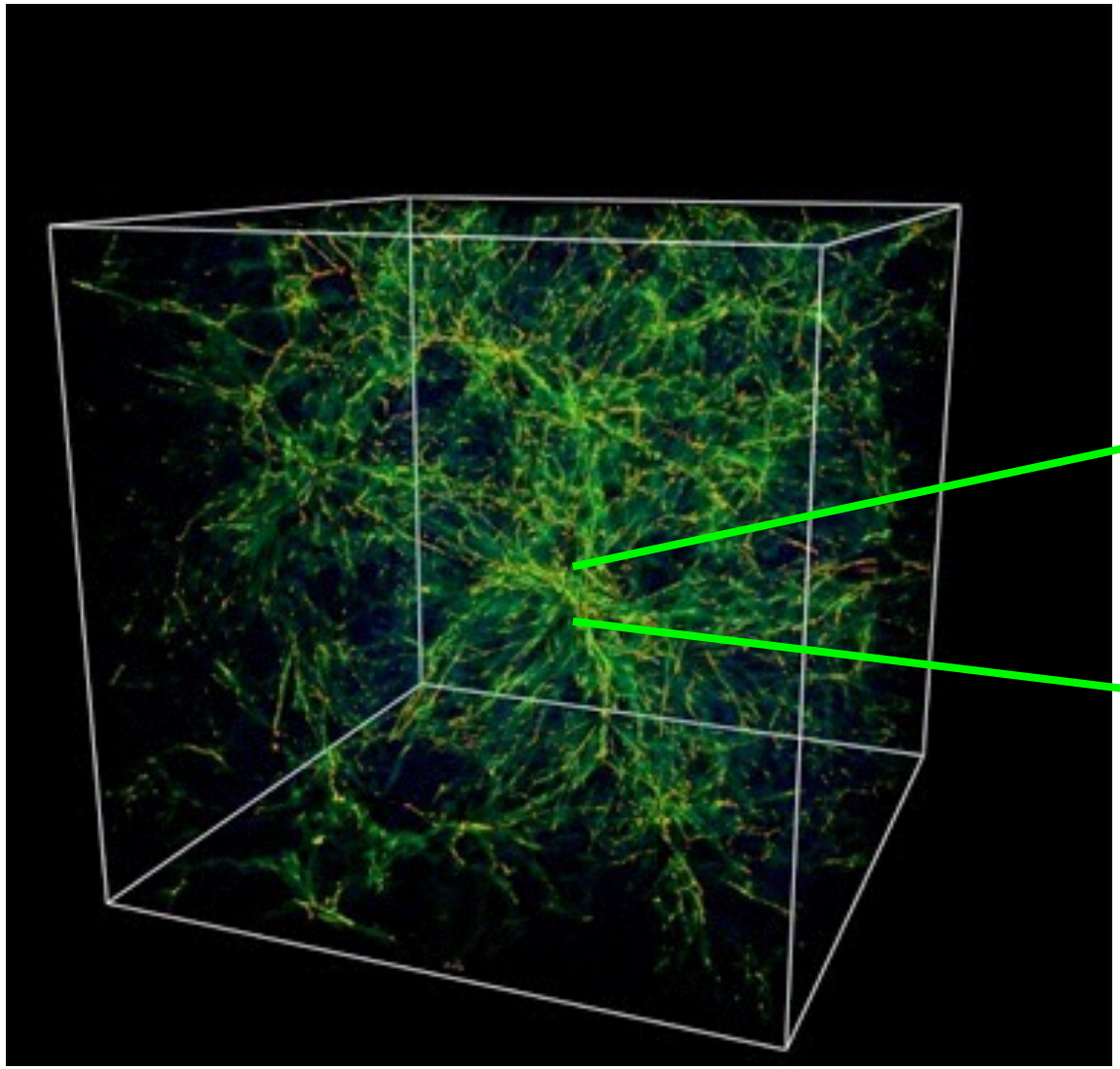
David Schlegel, Berkeley Lab

Outline

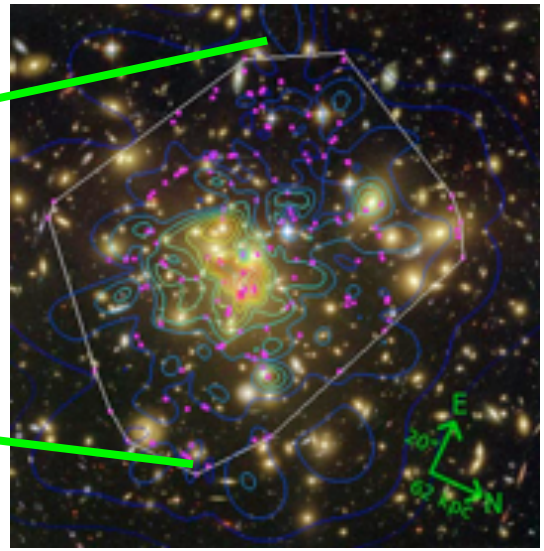
- Redshift survey objectives: mapping linear modes
- DESI goals + technologies
- Beyond DESI
  - DESI-II: 200M galaxies at $z < 2$
  - FOBOS: Lyman-alpha at $z > 2$
- Investments to keep us “on the curve”

Redshift survey objectives: Map all the linear modes

Cosmological information content is in the linear regime



linear perturbations
on scales > 10 Mpc at z=0



non-linear modes

Redshift survey objectives: Map all the linear modes

Cosmological information (dark energy, primordial Pk, neutrinos) containe the perturbative modes of the maps

II. LINEAR MODES

For a Gaussian random field with power spectrum P, in a periodic box where Fourier modes are well-defined, the error on a given power spectrum bin is given by

$$\sigma_P^2 = \frac{P^2}{N} \tag{1}$$

where N is the number of modes, counting the real imaginary parts at one $\mathbf{k}$ as 1. Therefore, we can *define* an effective number of linear modes for a survey to be given by the sum of signal-to-noise squared over band power estimates, i.e.,

$$N = \sum_i \left(\frac{P_i^{\rm signal}}{\sigma_i} \right)^2 , \tag{2}$$

We make the bands fine enough that this effectively becomes a numerical integral over k, μ, and z. The signal power is biased redshift-space linear power $(b+f\mu^2)^2 P_L$ suppressed by the anisotropic information damping factors introduced

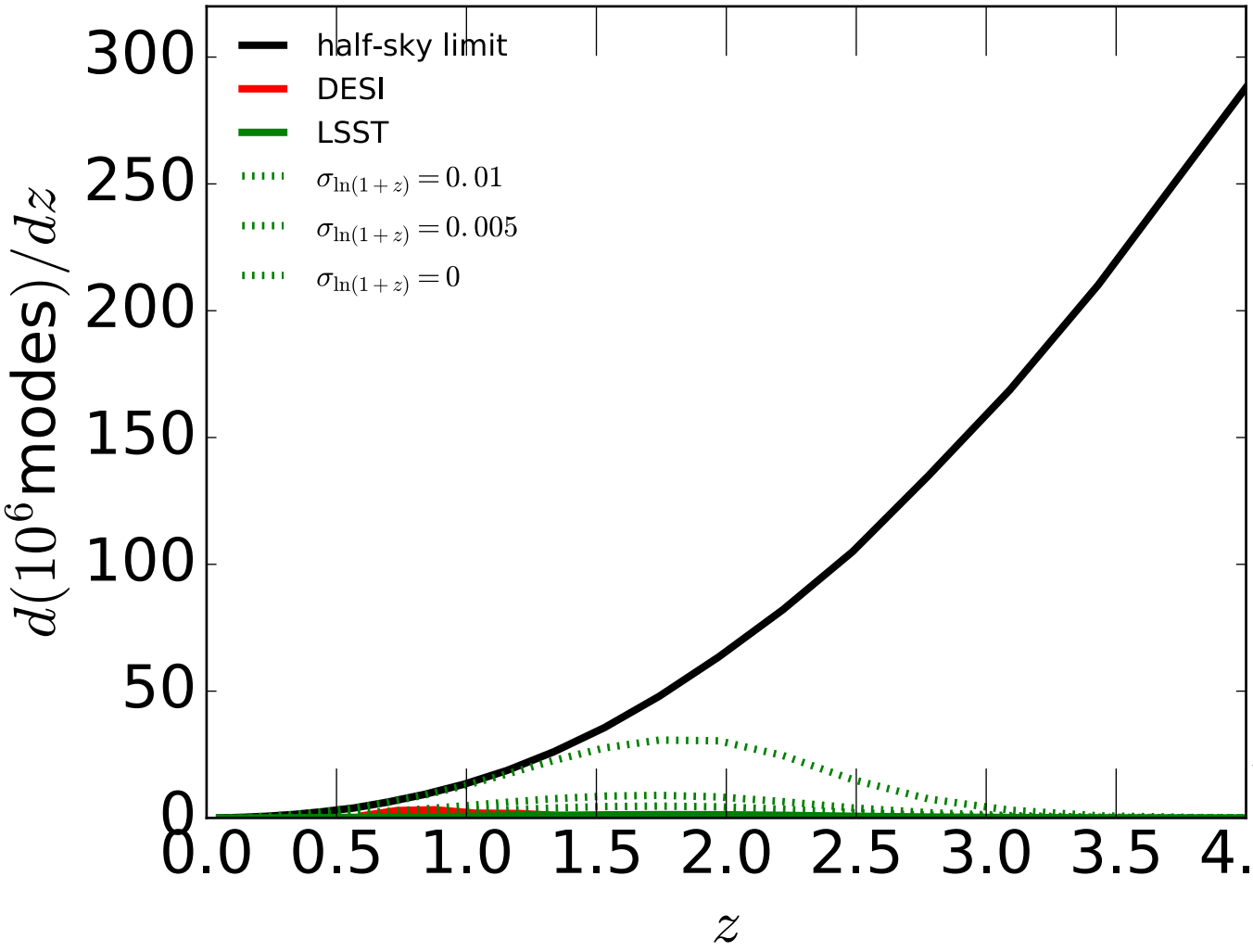
Font-Ribera, McDonald, Slosar in prep.

How many modes are there?

~2 billion linear modes from 0 < z < 4 (over 20,000 sq deg)

1.9 million modes to be measured by DESI

2.1 million modes to be measured by LSST



CMB ~few million modes

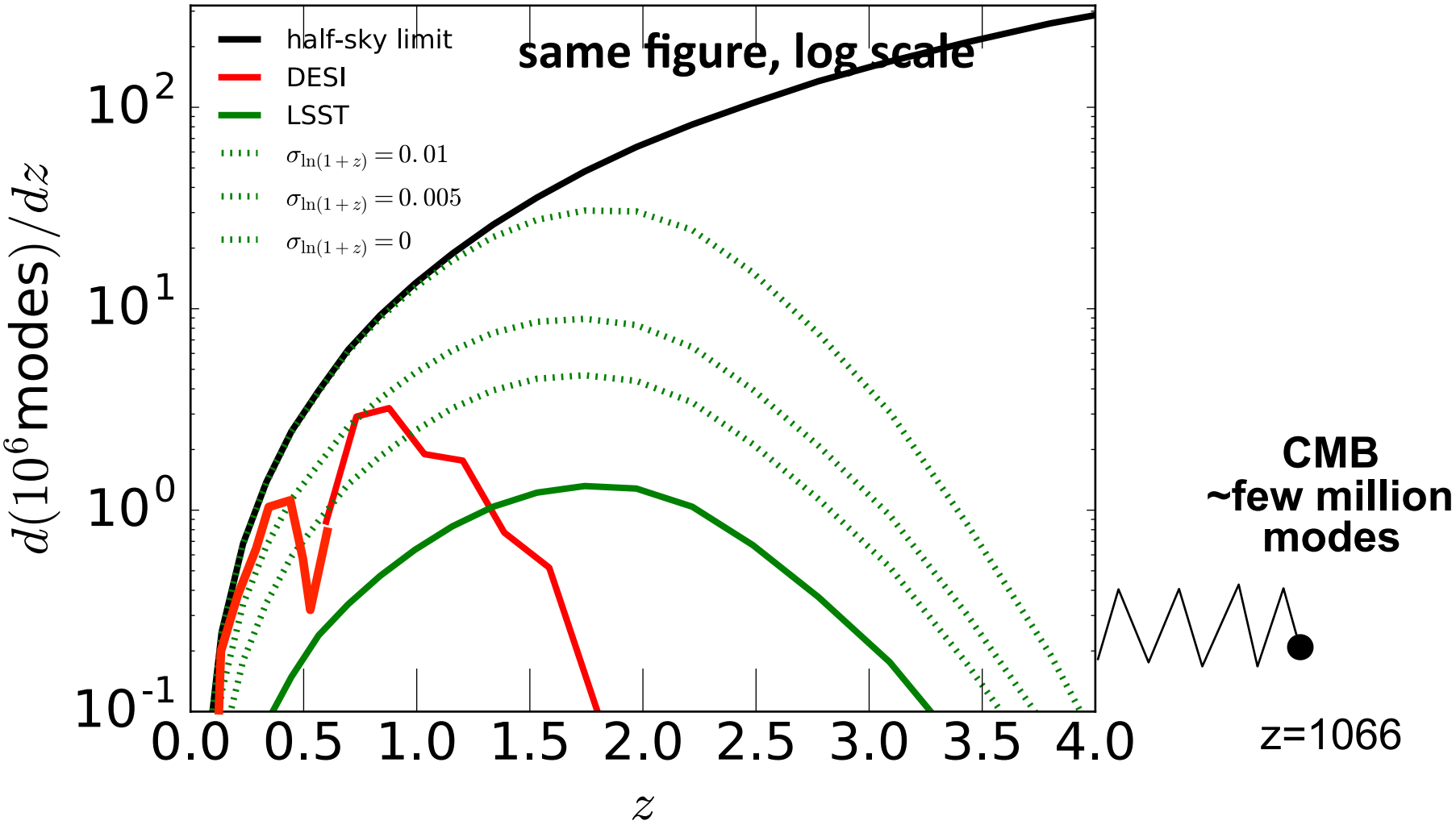
z=1066

How many modes are there?

~2 billion linear modes from 0 < z < 4 (over 20,000 sq deg)

1.9 million modes to be measured by DESI

2.1 million modes to be measured by LSST

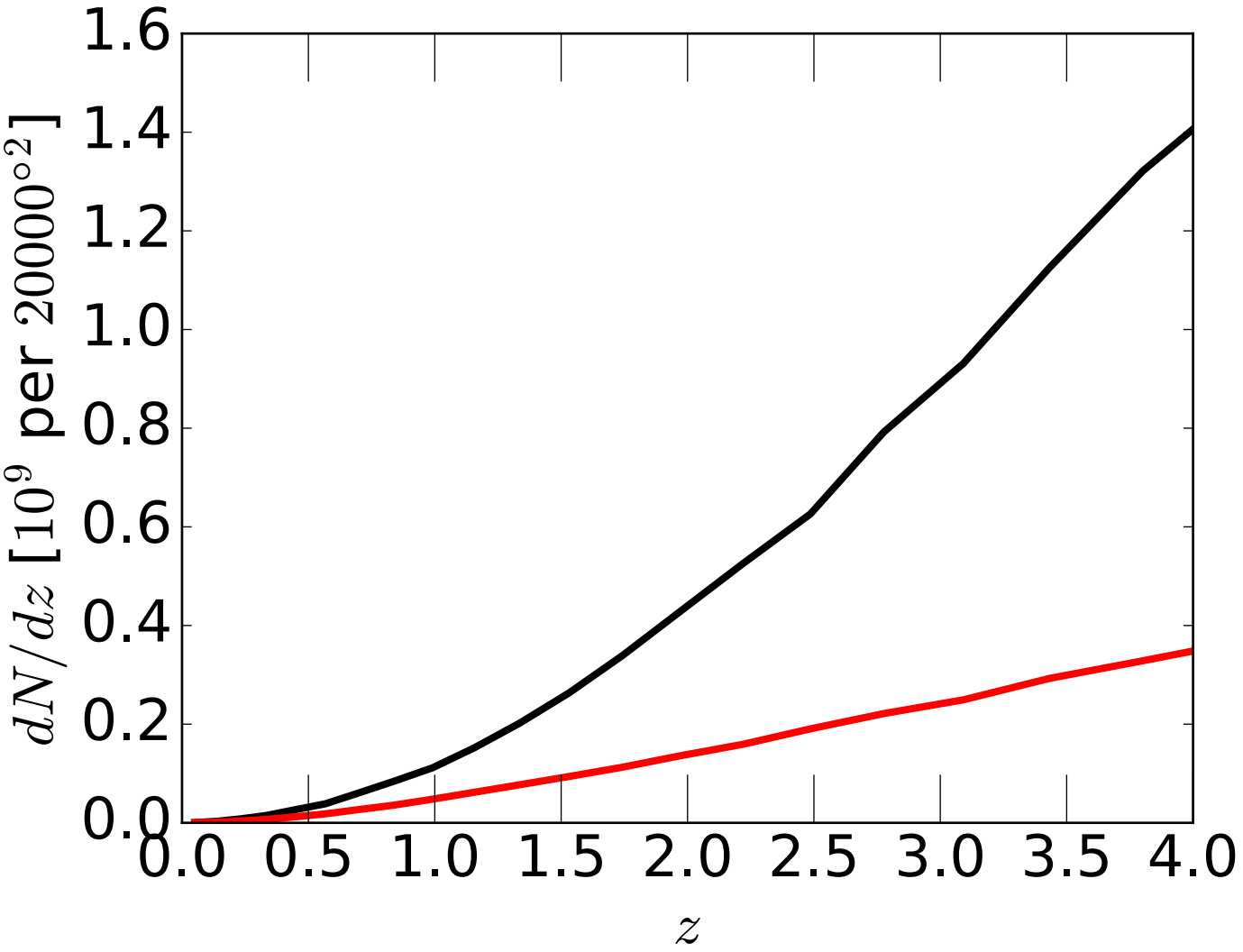


How many galaxies to measure these modes?

10 million galaxies 0 < z < 0.4

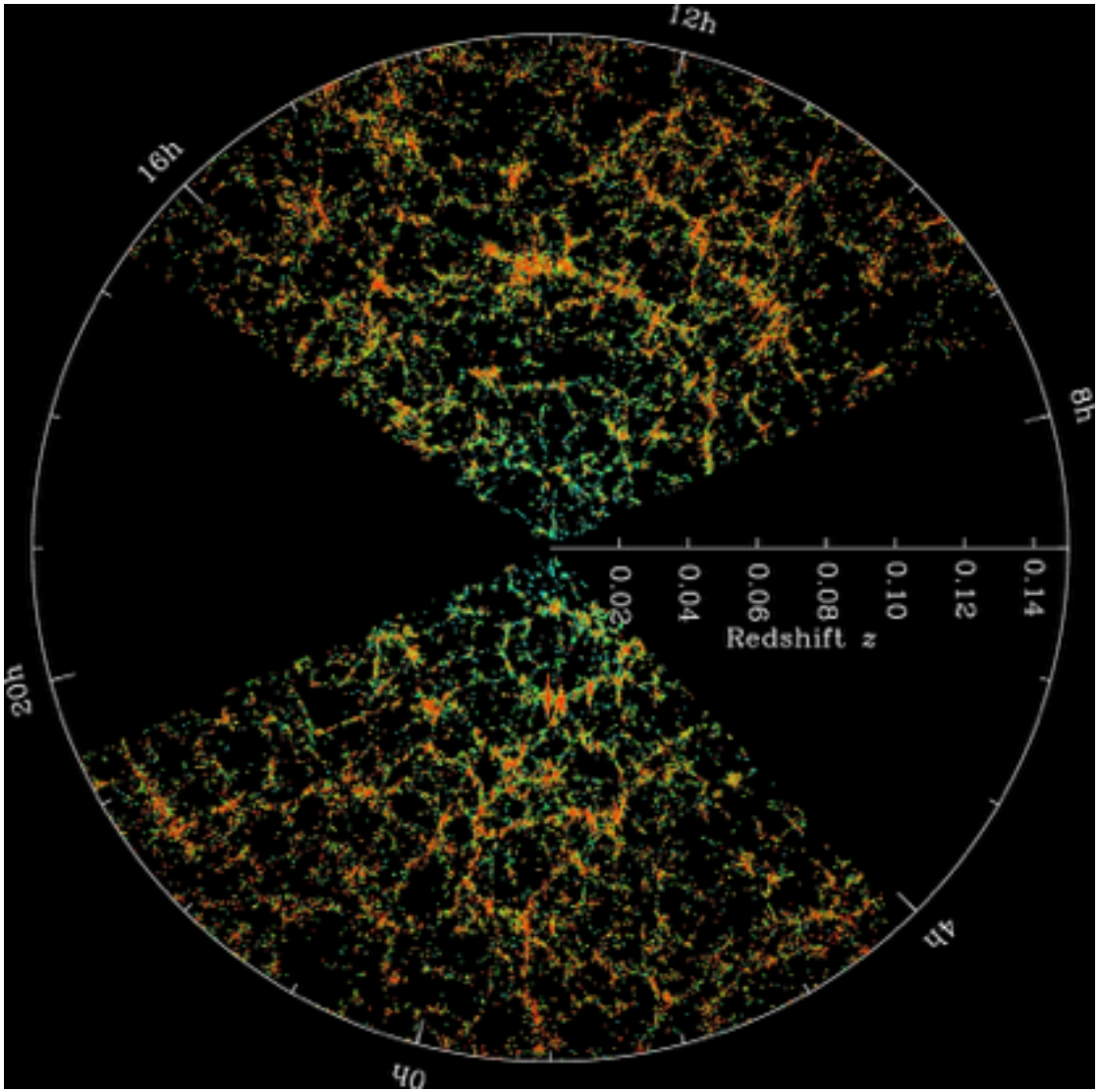
120 million galaxies 0 < z < 1.5

2 billion galaxies 0 < z < 4



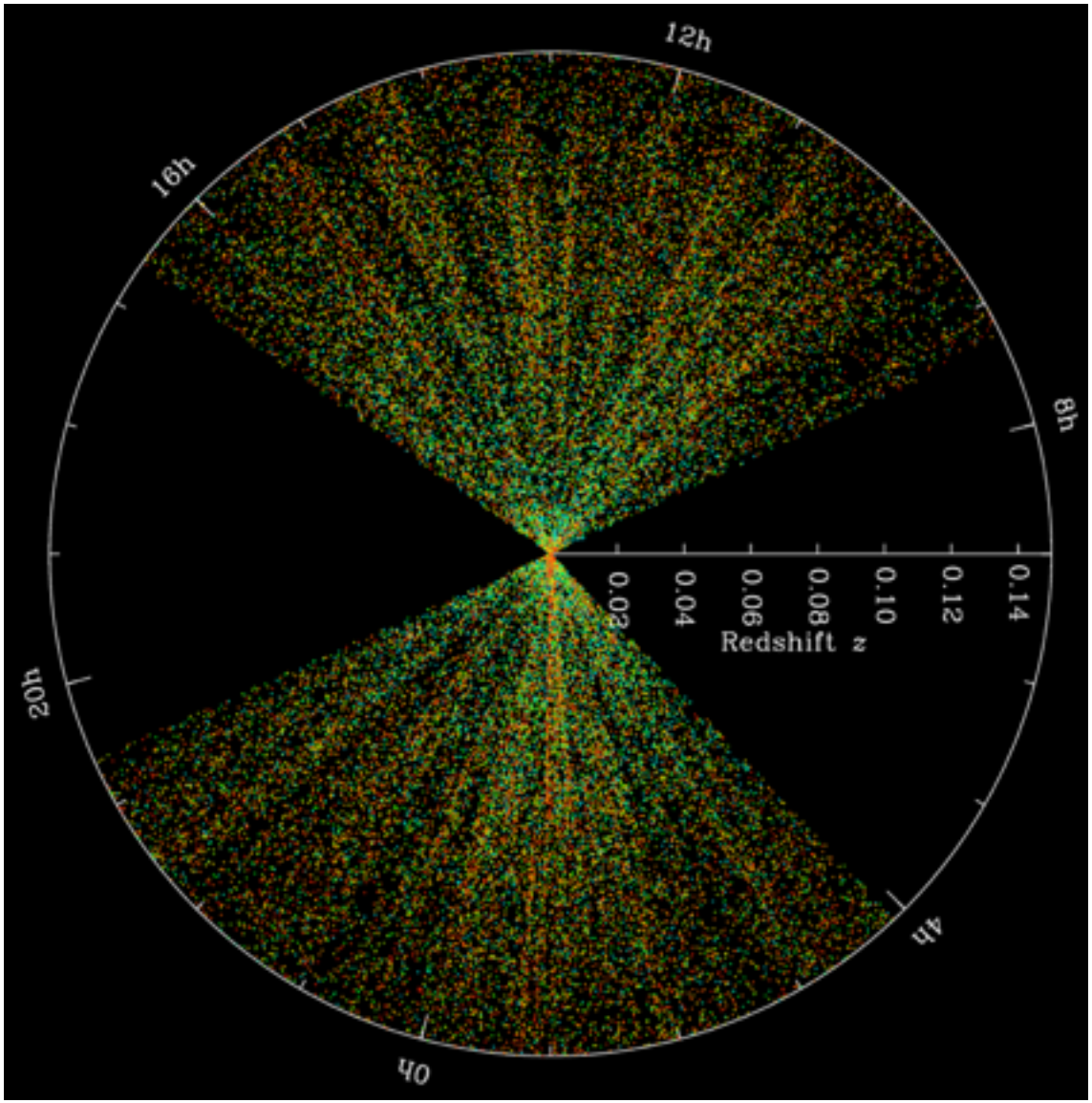
Redshift surveys necessary to map all modes

Redshift surveys Δcz ~ 300 km/s at z=0,
preserves information down to non-linear regime (e.g., small scales)



Redshift surveys necessary to map all modes

Photometric surveys Δcz ~ 10,000 km/s at z=0,
washes out many of the linear modes; not recoverable even w/numbers



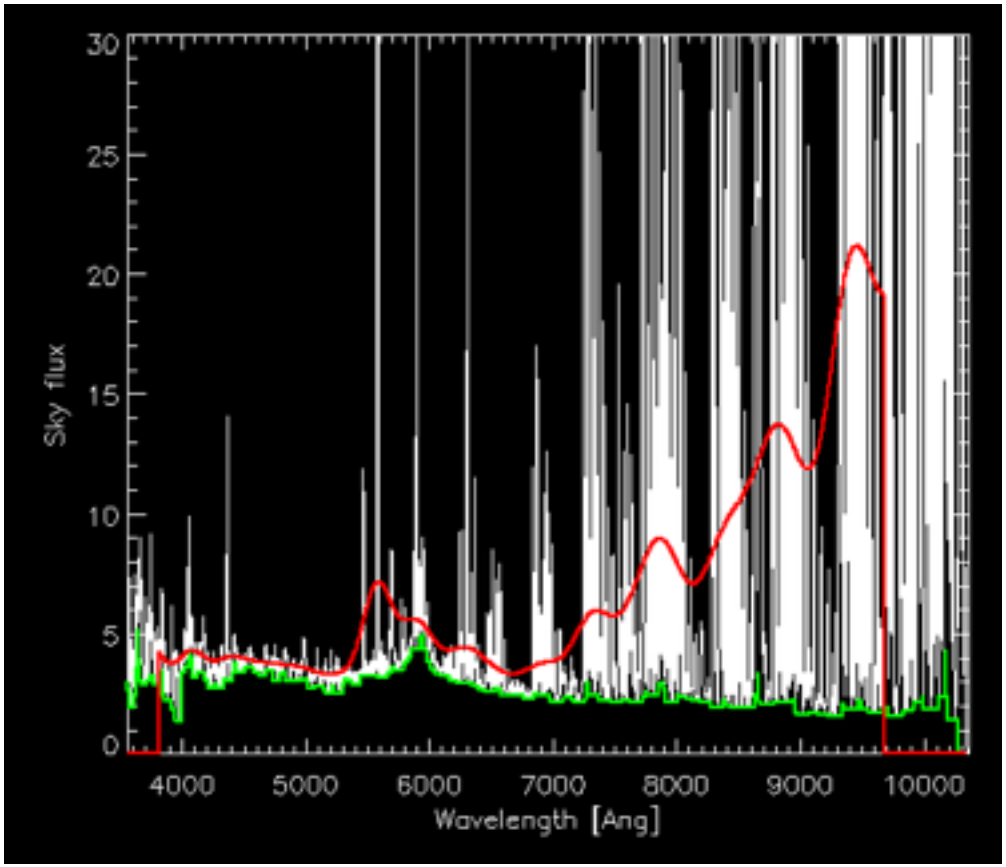
Low-resolution / photo-z redshifts pay a penalty

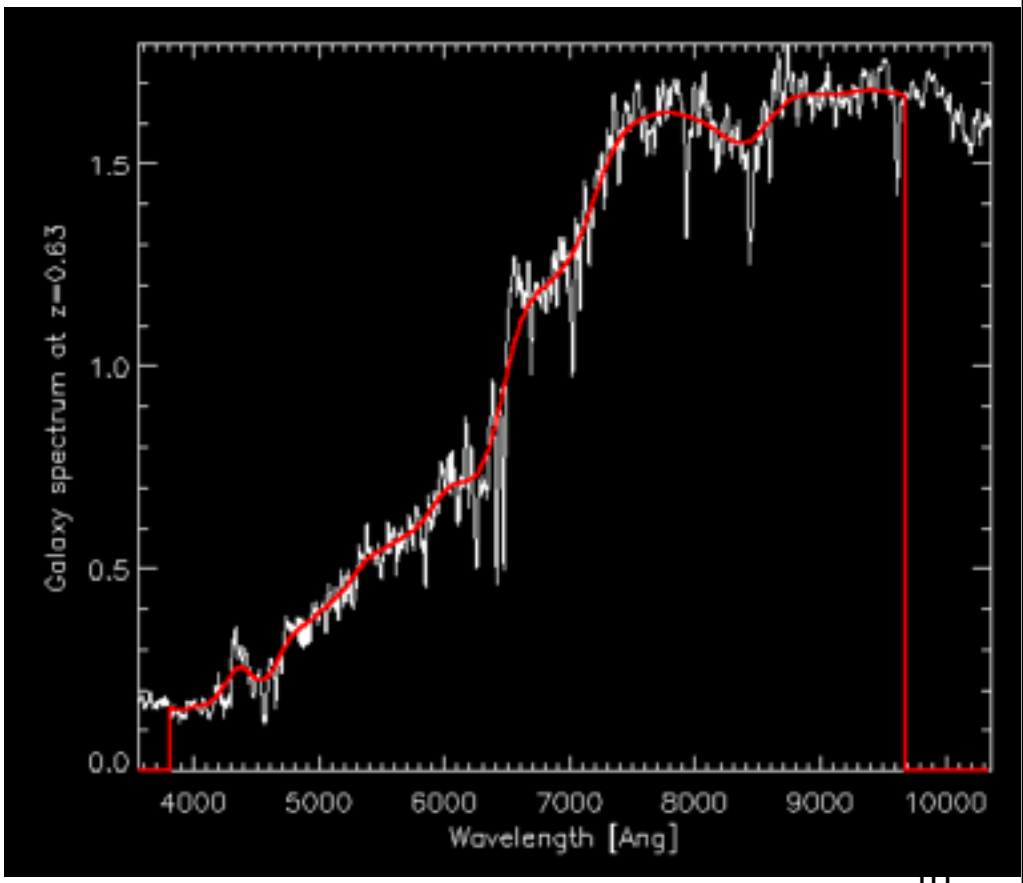
Spatial resolution helps to 1”

Spectral R > 3000 greatly reduces sky level by removing sky lines

(relevant for ground-based instruments)

Spectral R > 3000 improves redshift s/n



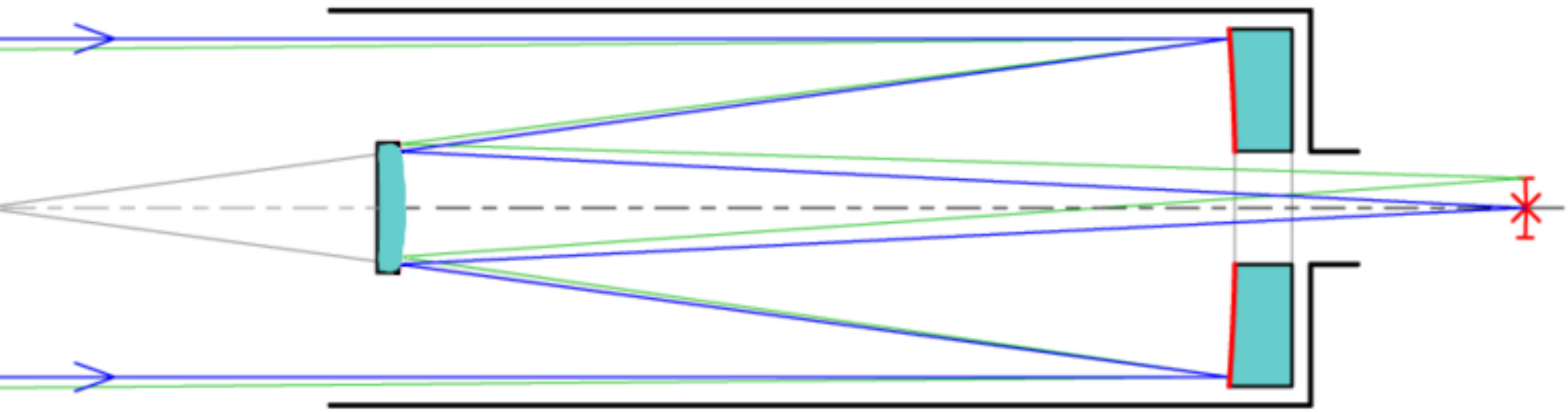


Redshift surveys are necessary to map all modes

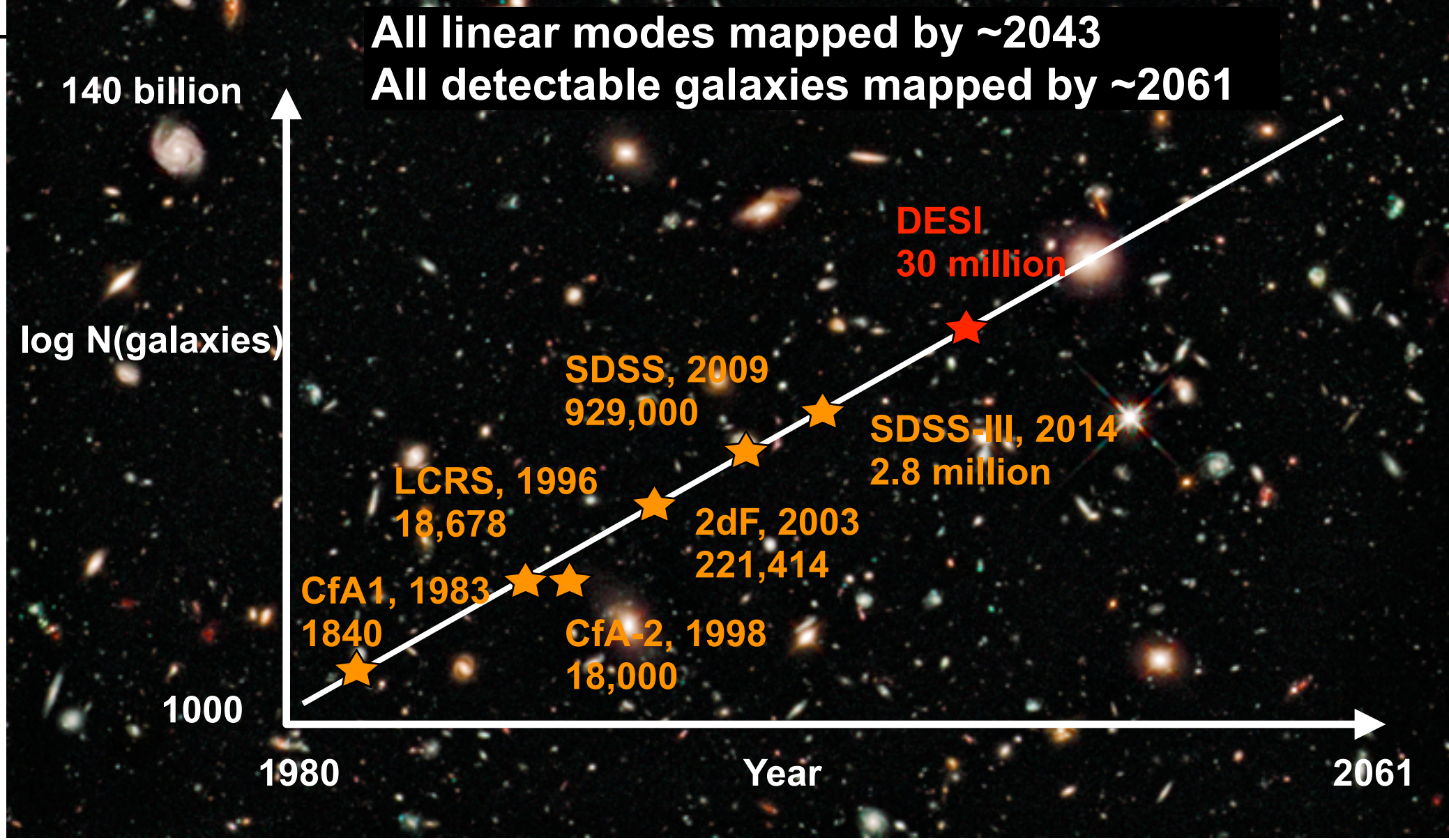
There are more objects of interest on a spectroscopic focal plane than on an imaging focal plane

~10,000 / deg^2 for imaging → information has saturated

~100,000 / deg^2 for spectroscopy



Redshift surveys increasing 10X every 10 years



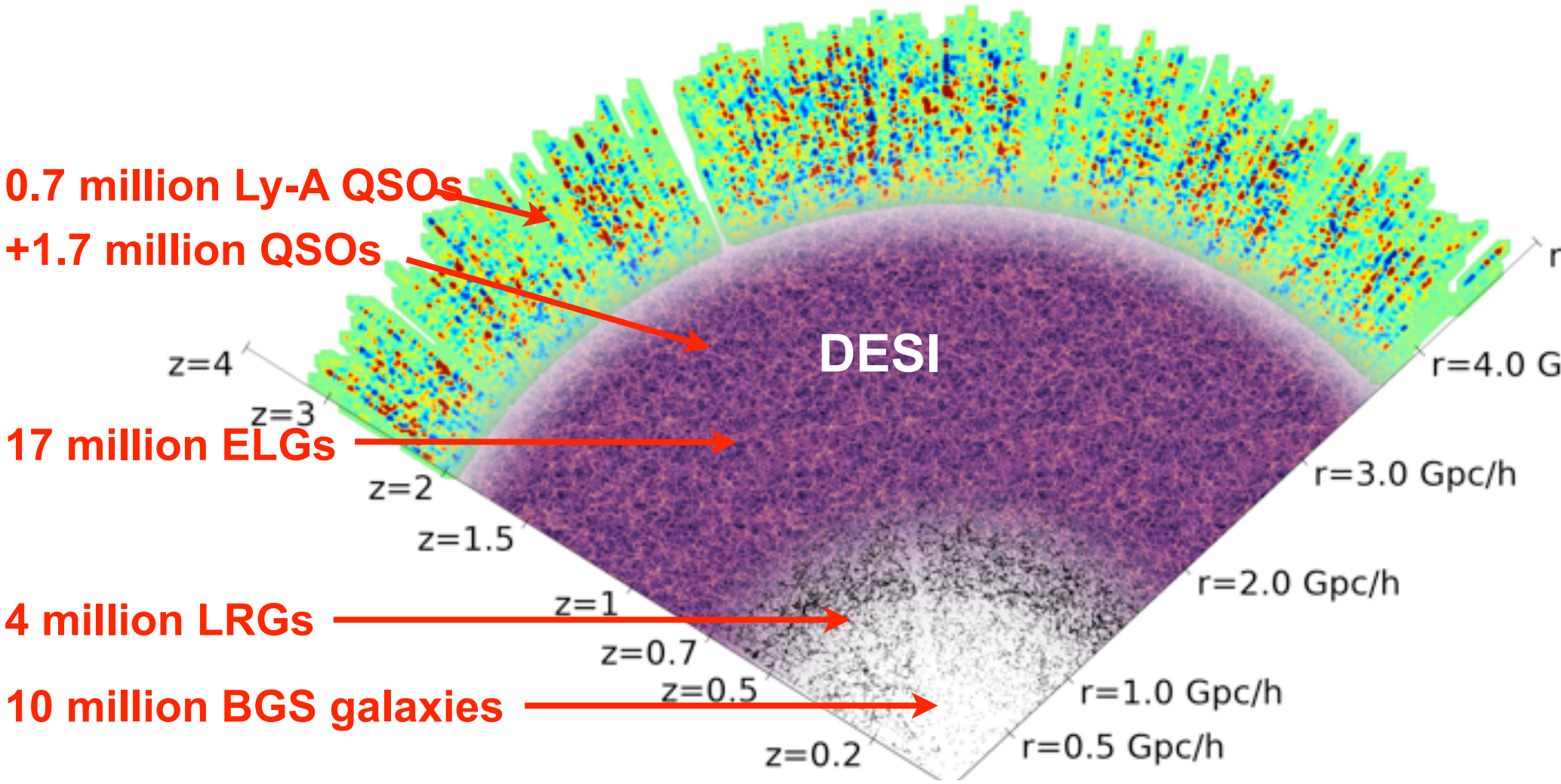
HST Ultra-Deep Field
10,000 galaxies / (11 arcmin^2)

DESI Goals + Technologies

4 meter primary
1 meter diam corrector
5000 fiber-robot army
200,000 meters fiber optics
10 spectrographs x 3 cameras

DESI Goals

35 million galaxy + QSO redshift survey

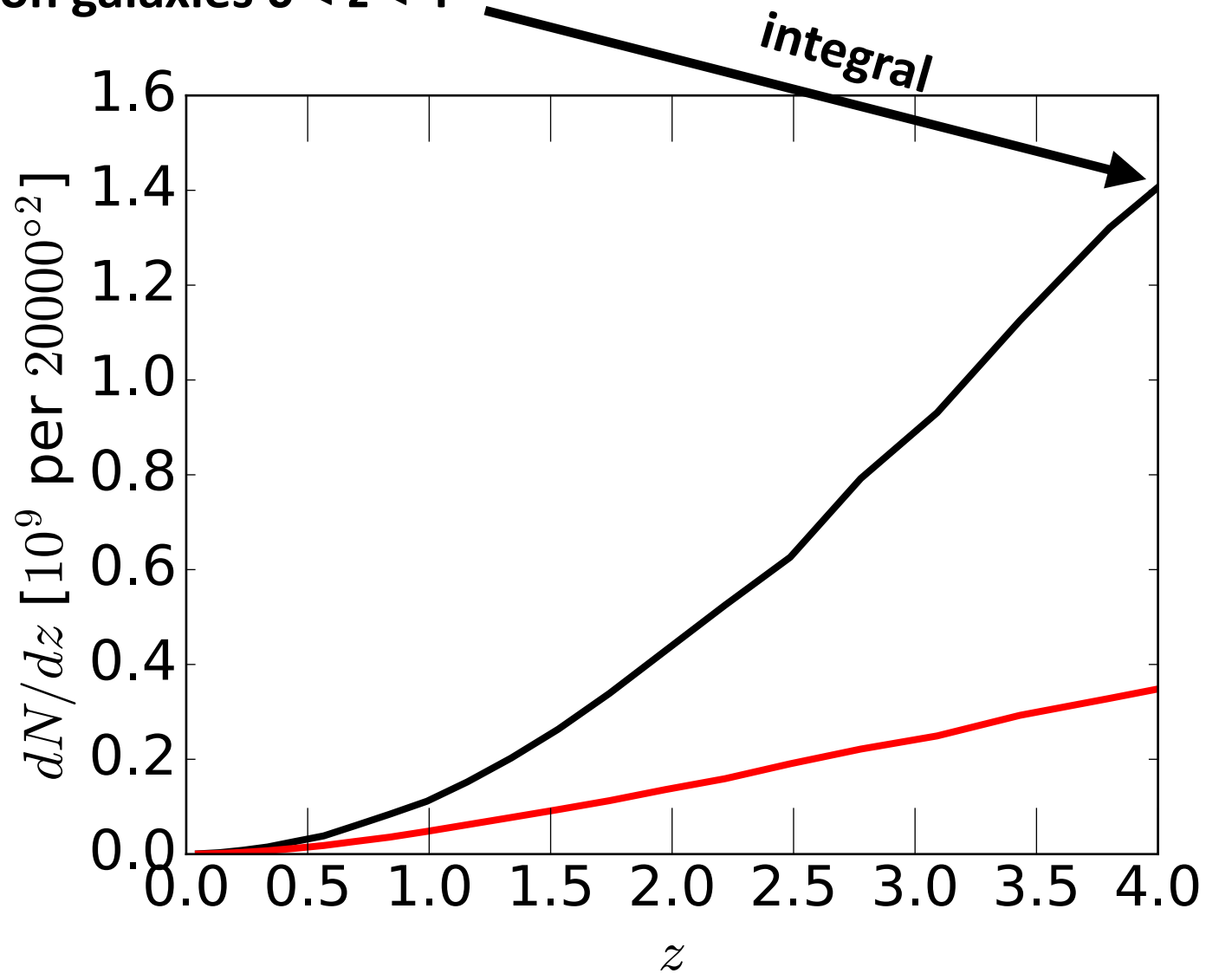


How many galaxies to measure these modes?

10 million galaxies 0 < z < 0.4 —> DESI will map ~100% of these

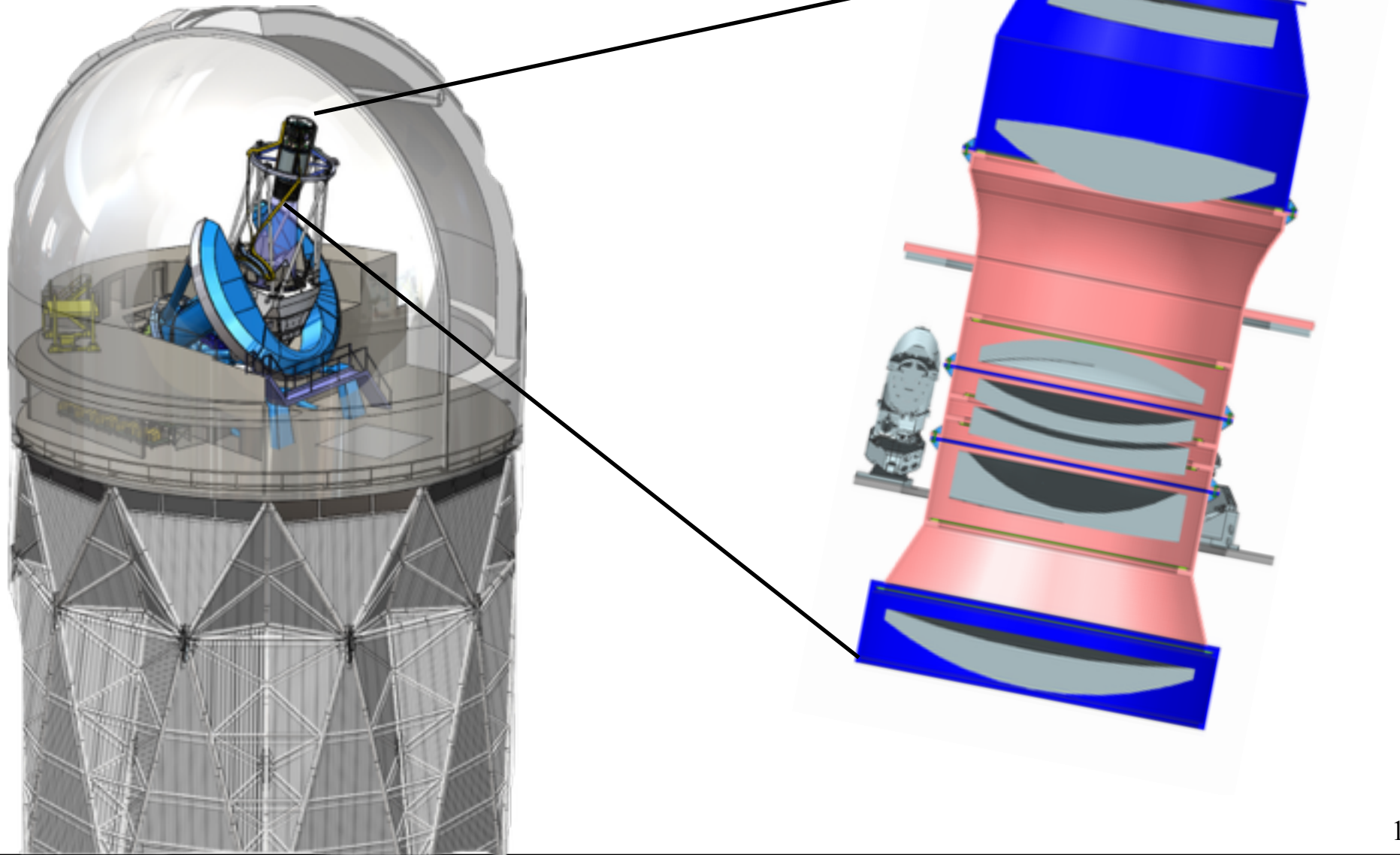
120 million galaxies 0 < z < 1.5 —> DESI will map ~10% of these

2 billion galaxies 0 < z < 4



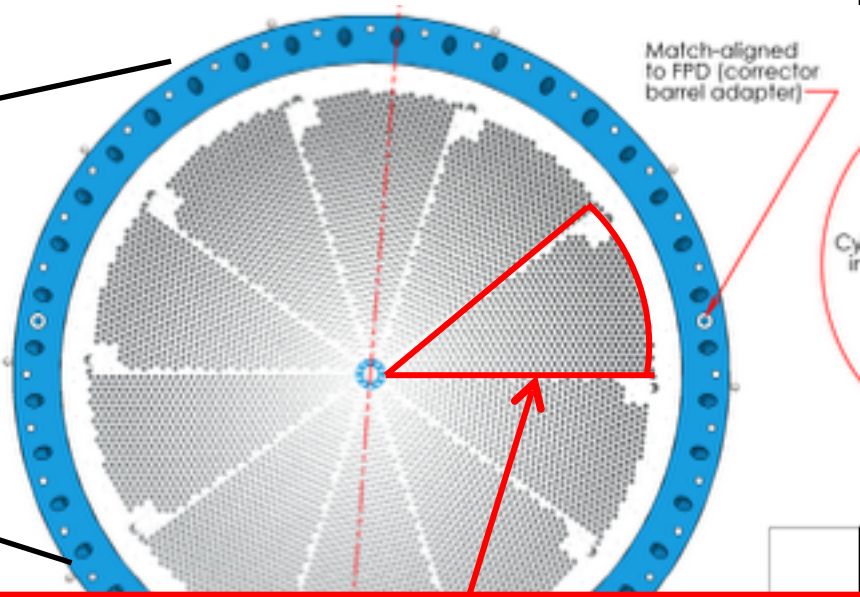
DESI Technologies

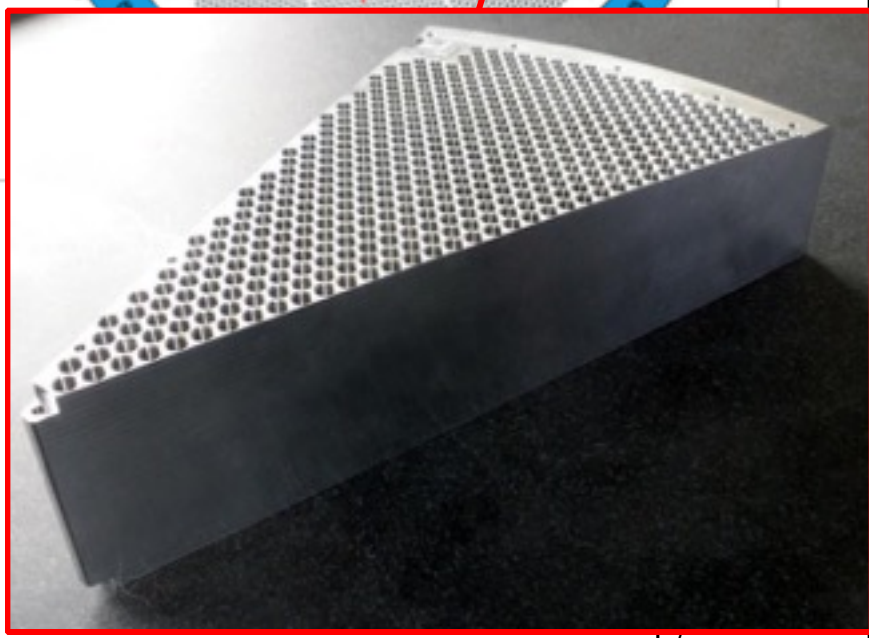
6-lens optical corrector, 1-m diameter, includes ADC



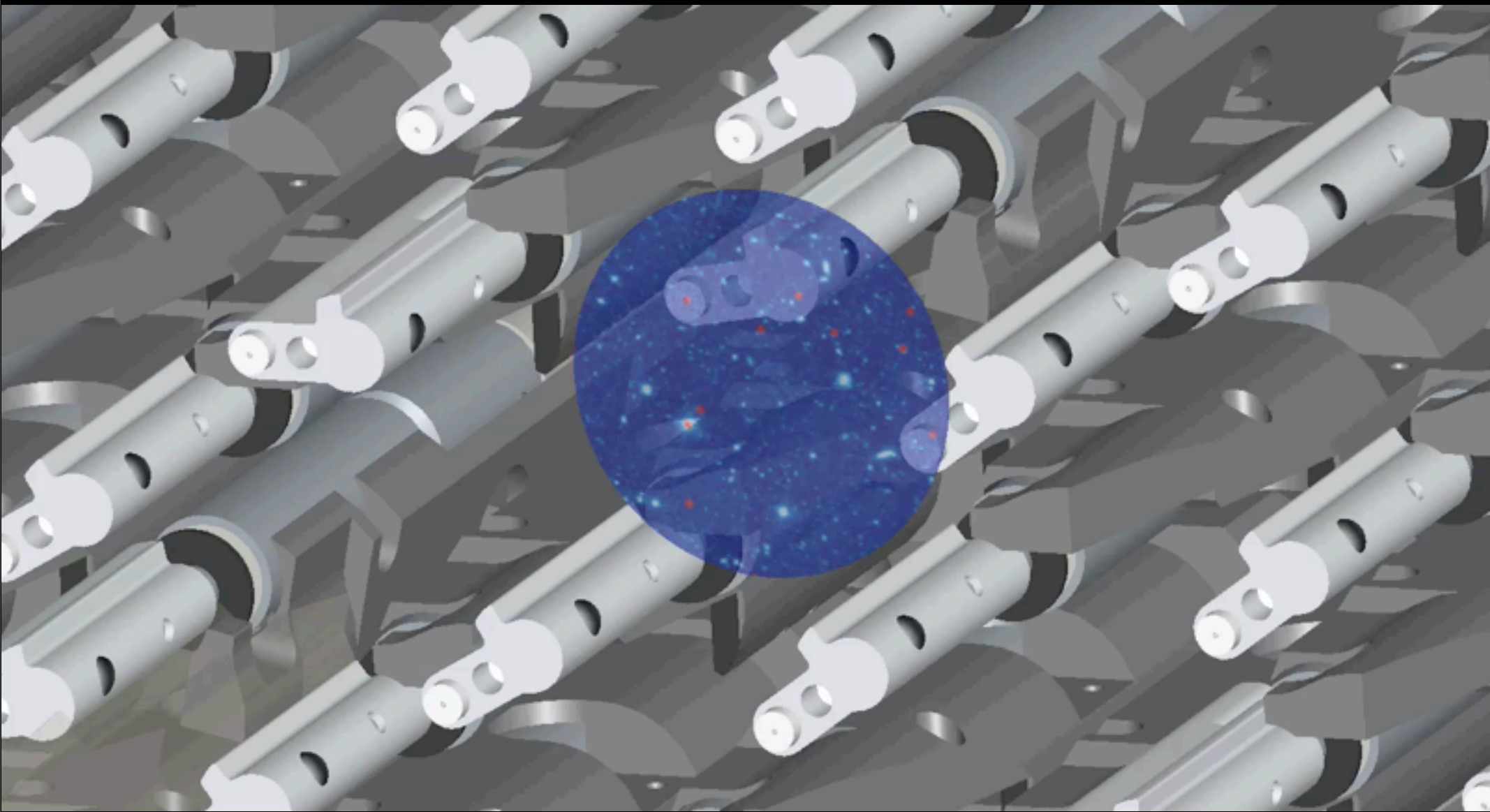
DESI Technologies

Focal plate mounting 5000 fiber robots



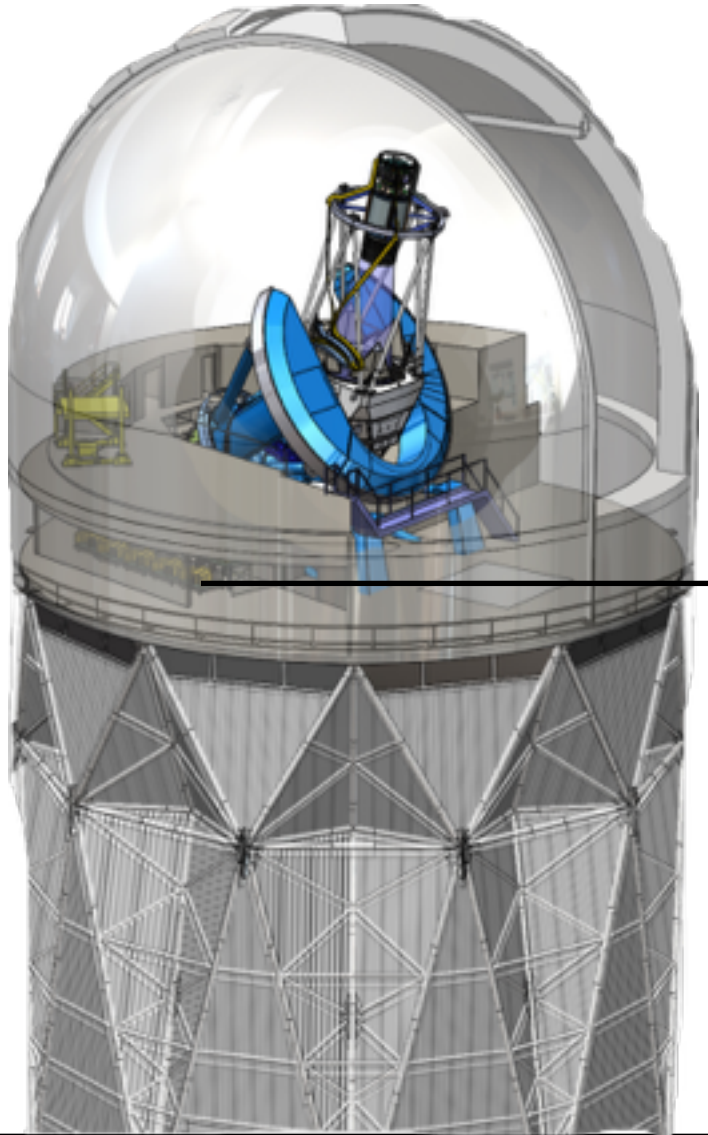


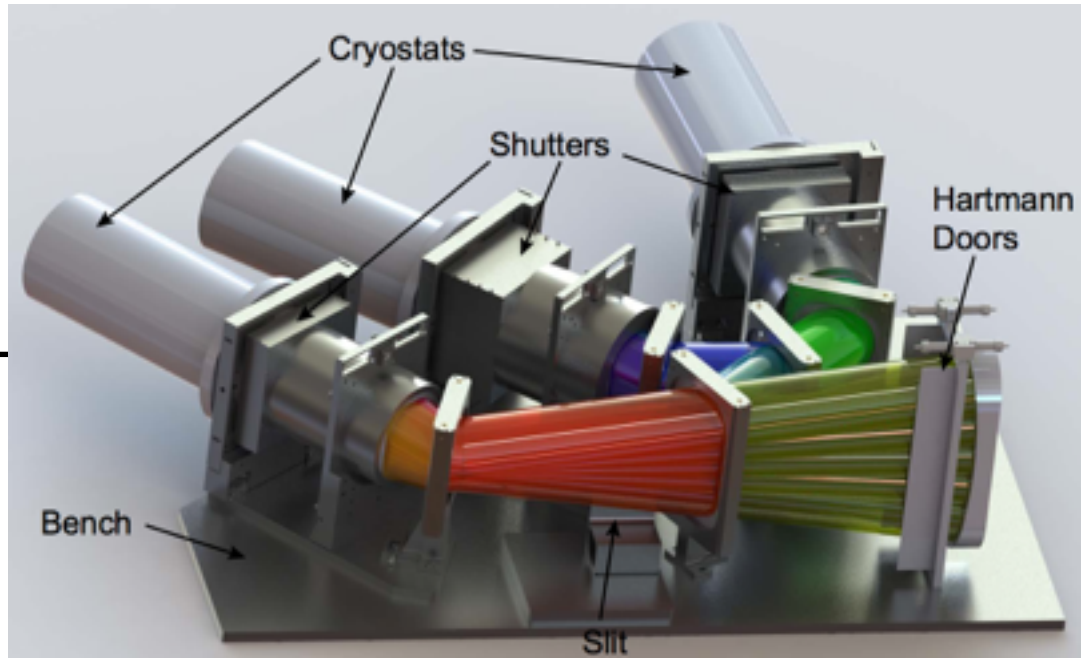
The robot army of DESI replaces hand-plugging of fibers



DESI Technologies

10 spectrographs X 3 cameras/spectrograph



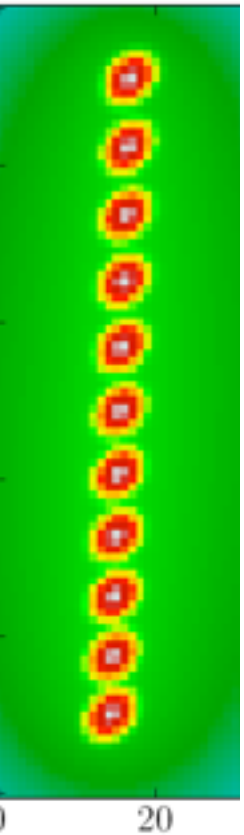


DESI Technologies

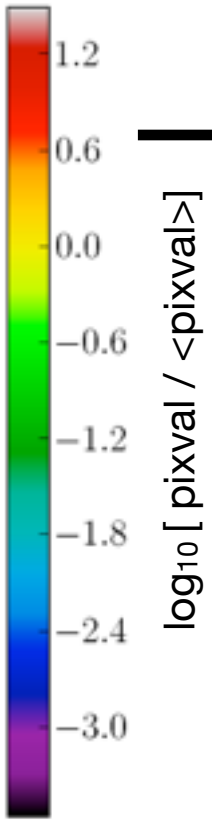
Forward-modeling of spectro data offers substantial improvements over the old-school, 20th-century, data reduction of SDSS-I

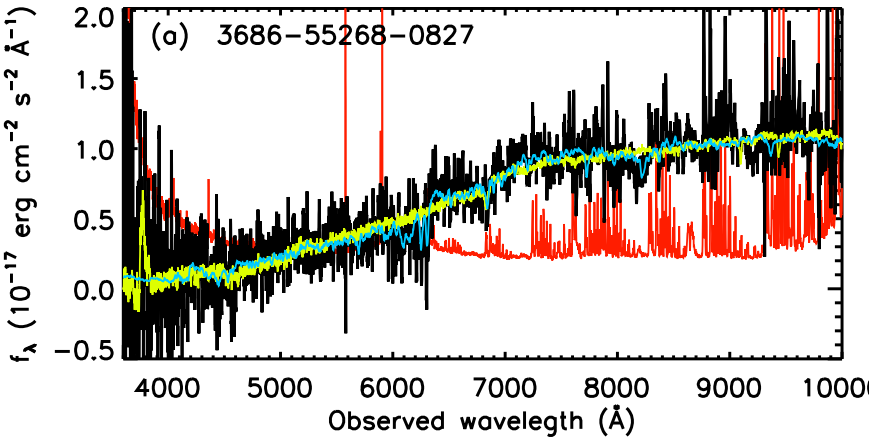
- **SDSS-I operated at S/N ~ huge**
- **SDSS-III/BOSS operated at S/N ~ 50**
- **DESI will operate at S/N ~ 10**

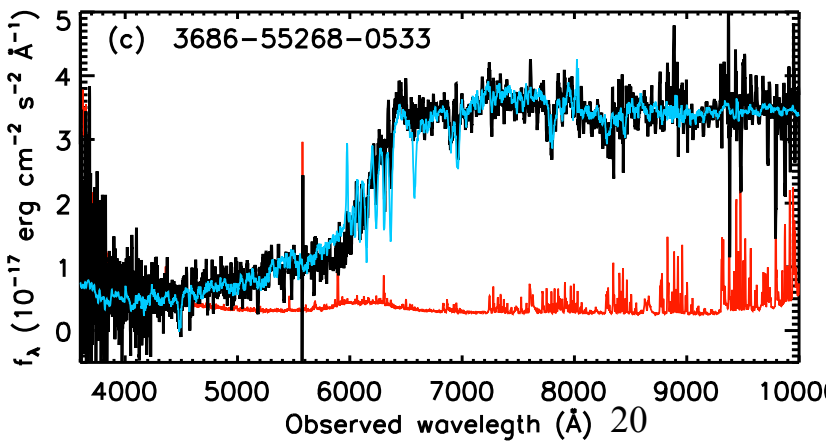
"data"



Model fiber PSF for SDSS1 @ 8500Å







The future of redshift surveys?

Modest improvements in capability from SDSS-I → SDSS-III/BOSS → DESI

How has capability improved?

- **CCDs → improved, esp. in the red/infrared**
- **CCD electronics → lower noise**
- **Stability of calibration systems**
  - **allowing better sky-subtraction, fainter objects**

Bigger gains have been in multiplexing

- **Optical designs for wider fields on telescope & in spectrographs**
- **More fibers, hand-plugged → massively-parallel robots**

Technical challenges are cost effectiveness

Pre-SDSS → SDSS revolution

Multiplexing from 1-30 objects → 640 objects

using fiber-fed spectrographs

In 2015, SDSS has collected more galaxy redshifts (2.7M)

than all other telescopes on earth combined

Cost models for multi-objects spectrographs scaling from DESI

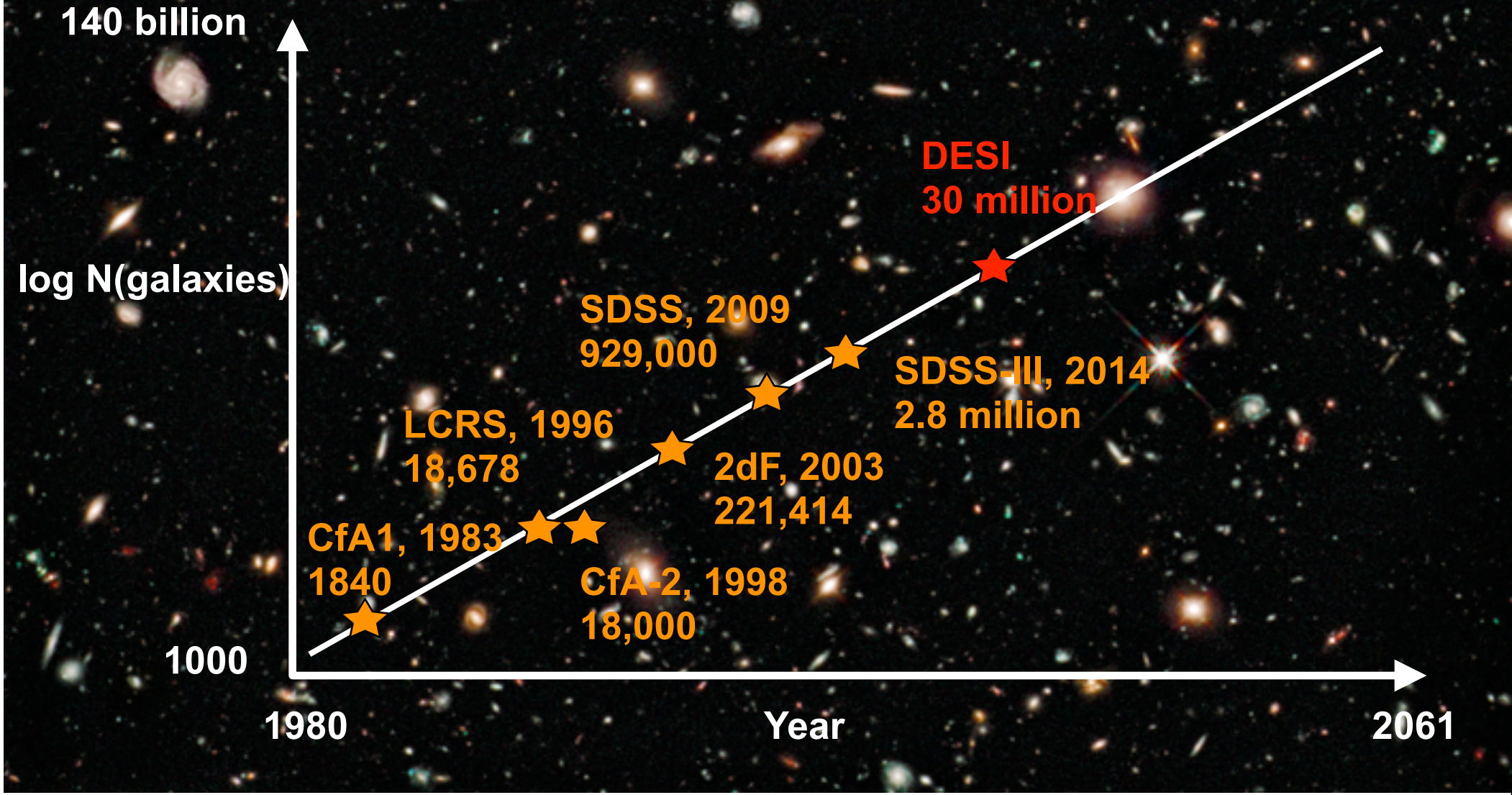
	Cost for 1% improvement
Telescope + corrector ($40M + $10M) * (Mirror area / 4-m)^2	+$200k + $50k
Focal plane + spectrographs $1000 X N_{fiber} + $1M X ($N_{fiber}$/500)	+$150k
Operations $6M/year X 5 years	+$300k

DESI cost model is reasonably well-balanced

Most improvement would come from more fibers,

but not possible on DESI given other design constraints

Future investments to keep us “on the curve”?



Future investments to keep us “on the curve”?

Fiber robot costs

→ Pick-and-play fiber positioners (2dF, MMT, …) do not scale

→ Fiber robots w/ 1 robot per fiber scales

~$10,000 / fiber for Subaru/FMOS in ~2006

~$2000 / fiber for Subaru/PFS in ~2013

~$700 / fiber for DESI in ~2015

Future investments?

→ DOE started R&D in 2006 with LBNL LDRD support, followed by DESI development

→ Continued R&D would further reduce per-robot costs

Two possible near-term redshift survey concepts

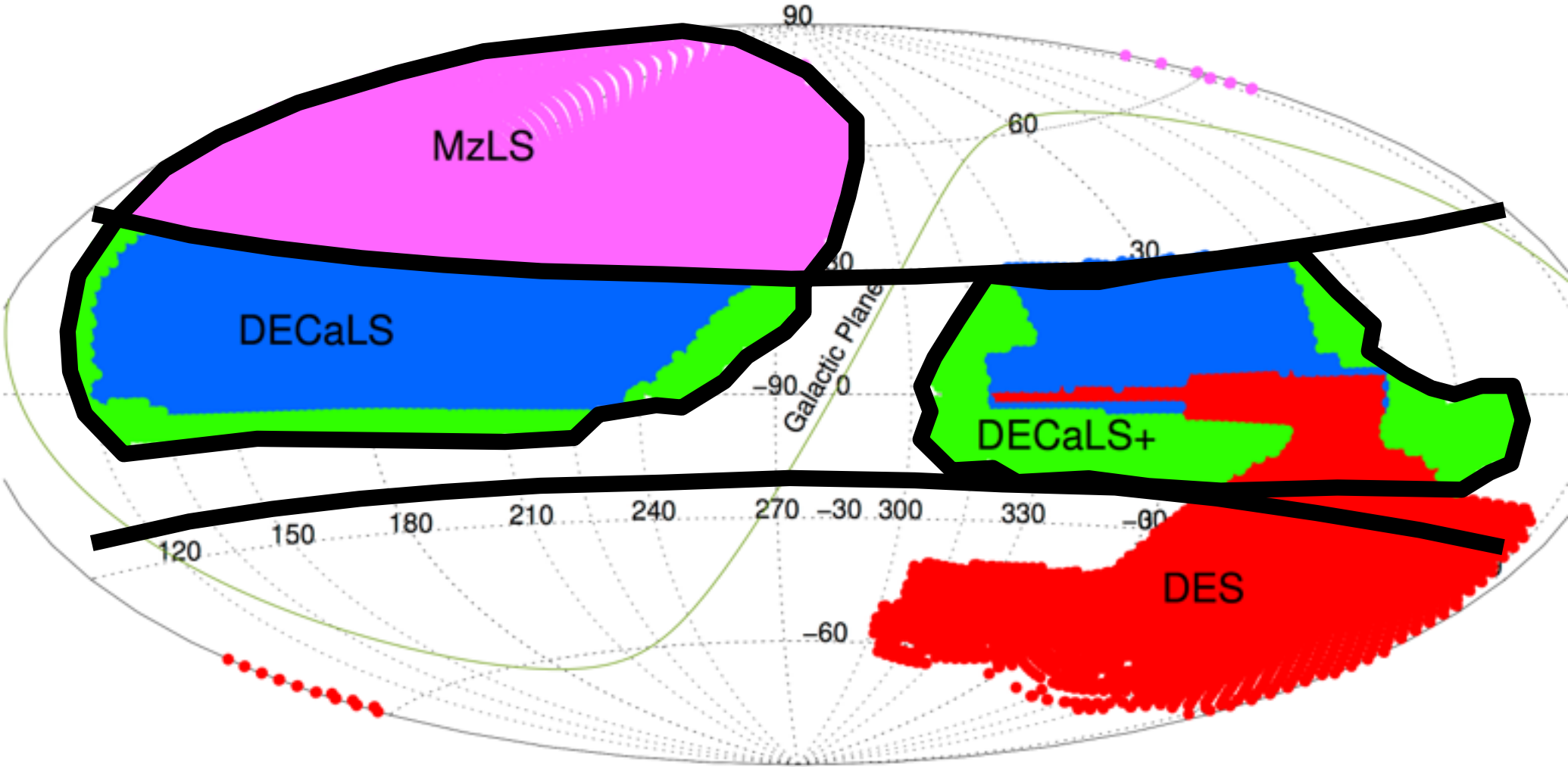
DESI-II + LSST for z<2

Option 1: DESI @ Kitt Peak, LSST @ Cerro Pachon

10,000 sq deg footprint equatorial

Option 2: DESI @ Cerro Tololo

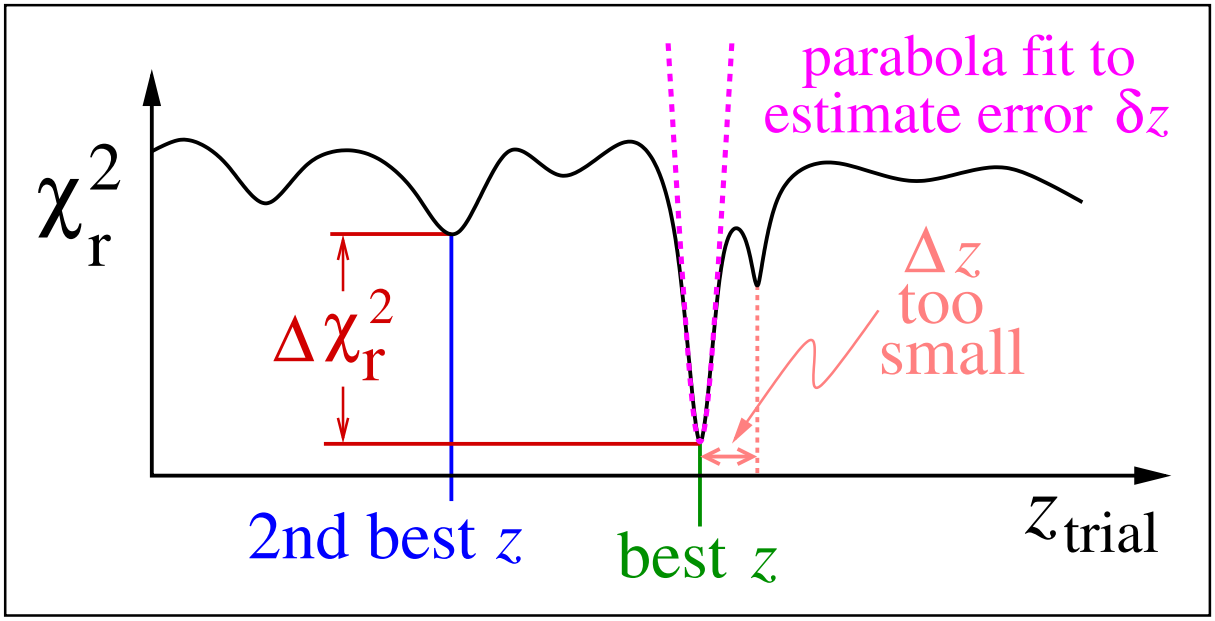
14,000 sq deg footprint equatorial + south



DESI-II + LSST for z<2

DESI-II + LSST for z<2

1. **Retain DESI @ Kitt Peak with 10,000 sq deg overlap, or move DESI instrument from Kitt Peak -> CTIO**
   - Optics study from Tim Miller (16 Sep 2014) shows no changes needed to the optics (in fact, it's better there!)
2. **Re-furbish instrument with faster electronics**
   - Probably necessary for shorter exposures
3. **Target ~200,000,000 galaxies with the best photo-z's**
   - LSST will have a parent sample of ~10 billion galaxies
4. **Turn photo-z's ➔ spectroscopic redshifts**
   - Δz~0.03 ➔ Δz~0.001



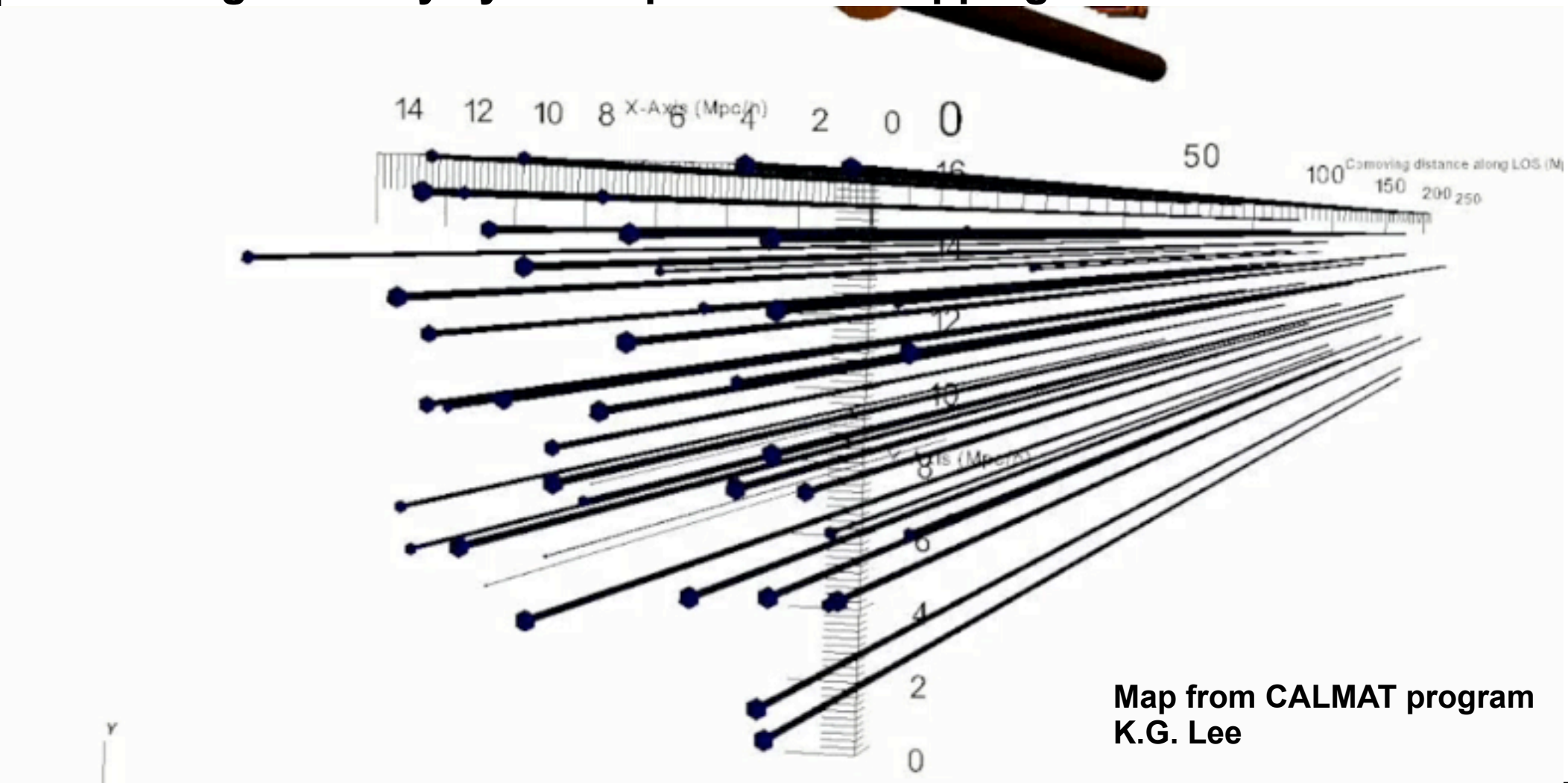
The trick:
DESI operates at S/N > 7
DESI-II at S/N > 3

Bolton, Schlegel et al. 2012

FOBOS @Keck for z>2

FOBOS @Keck for z>2

1. Utilize Cass or Nasmyth focus at either Keck telescope
2. 1000-fiber robotic focal plane, using DESI technology
3. DESI spectrographs
4. High-density Lyman-alpha forest mapping at z > 2

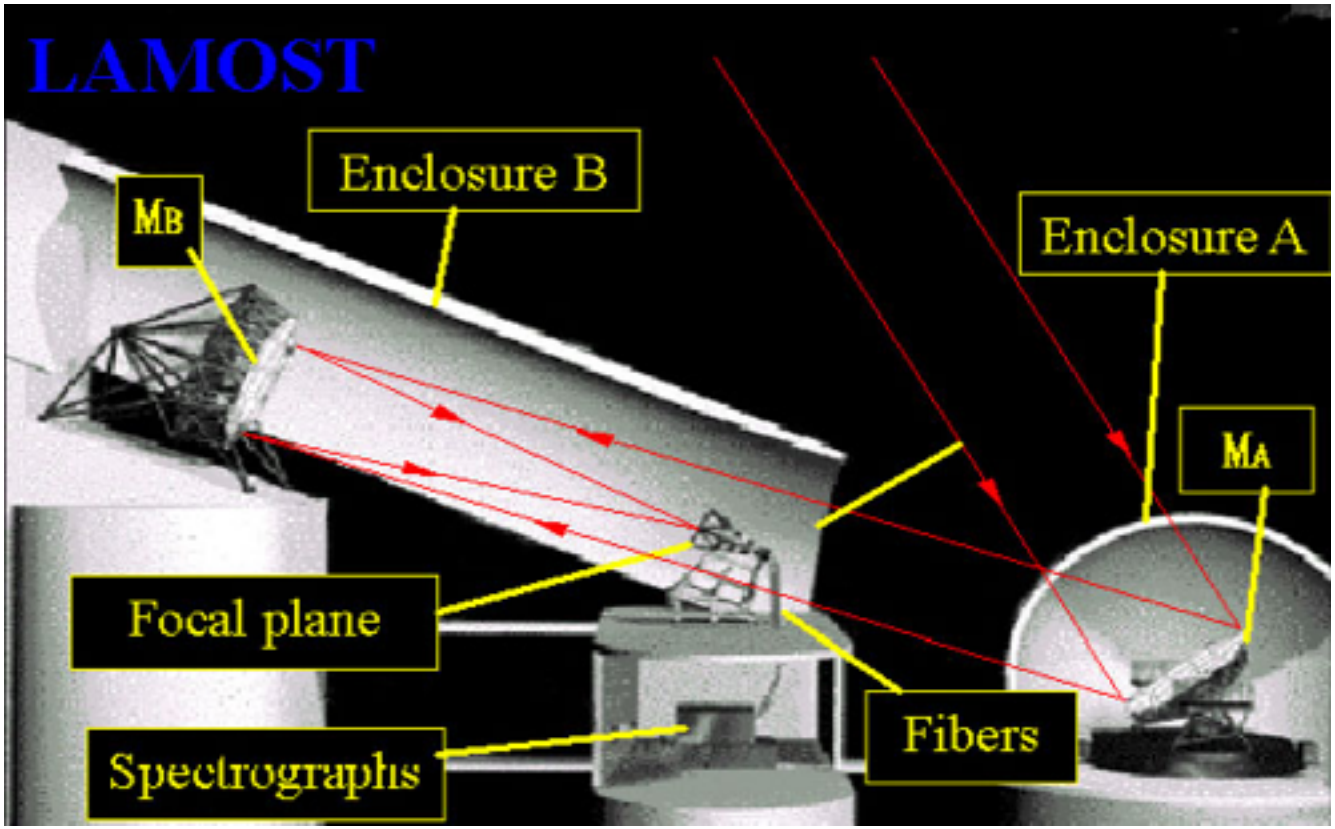


Map from CALMAT program
K.G. Lee

Longer-term redshift survey concept

What's possible with current tech?

1. **Optical design from LAMOST/Guoshoujing telescope**
   - ~2X aperture of DESI
2. **DESI fiber positioners**
   - 5X fiber positioners (25,000)
3. **Survey speed increase 10X for galaxies at z < 2, 5X for Lyman-alpha forest at z > 2**



Summary

Linear modes for cosmology

— DESI will map ~100% of modes at z < 0.4

~10% of modes at z < 1.5

~2% of modes at z < 4

— DESI-II + LSST could map 100% of modes at z < 1.5

—"Beyond DESI" need only map ~2 billion galaxies at z < 4

If the photons are valuable…

Spectroscopy is cost-effective use of those photons

For this Cosmic Visions Process…

DESI-II + LSST redshifting should be demonstrated/simulated